NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
Office of Space Science and Applications
Launch Vehicle and Propulsion Programs Division
Contract NSR 31-001-078

SOLAR ELECTRIC SPACE MISSION ANALYSIS

Progress Report for the Period

1 January through 31 March 1967

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Approved by: J. P. Layton
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15 July 1967

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CONTENTS

I. INTRODUCTION

A. General

During the period 1 January through 31 March 1967 research on solar electric space missions concentrated in the following areas

(1) continuing development of Gordon 1, heliocentric optimization program, and Item, n-body trajectory program.

(2) production runs on the Jupiter flyby solar electric mission using Gordon 1.

It is anticipated now that work on this contract can be completed by 30 September 1967 instead of 1968 as originally planned.

B. Personnel

This program is under the overall direction of Mr. J. P. Layton for mission aspects and Professor P. M. Lion for trajectory analysis aspects.

Dr. C. N. Gordon of RCA has been with us on a full-time basis during this period. His efforts have been directed toward the further development and improvement of Gordon 1. He has been assisted in this by Mr. A. E. Miller.

Mr. J. H. Campbell of AMA is continuing to adapt the n-body Item for solar powered spacecraft.

Mrs. A. B. Shulzycki has been responsible for data runs for the Jupiter flyby. This effort has provided an exercise of the Gordon 1 program over a range of realistic parameters.

Dr. M. Handelsman who has been with us on a part-time consulting basis, has been concentrating his efforts on the space communications systems considerations of solar electric missions, especially radar systems for detection of asteroids.

Mr. G. A. Hazelrigg, our Ph.D. candidate, returned from Jet Propulsion Laboratory on 1 February where he had been direct liaison on solar electric missions. He will now concentrate his efforts on his thesis work in powered planetocentric maneuvers.

A list of personnel currently associated with the Program is provided in APPENDIX A.

C. Princeton University Computer Center

At present charges for the use of University computers is covered in the indirect expenses. The ASMAR Program, which depends heavily upon computers, has greatly benefited by this policy. As of July 1, however, the University has been notified that it will be required to institute direct charging for all computing unless it can demonstrate a clear advantage to the government by retention of present or some alternative method. Direct charging would have a great effect on this contract. Since no funds were provided specifically for computing, it will be necessary to restrict production runs which involve large amounts of time. The key programs, Gordon 1 and ITEM, will continue to be developed to provide an exportable capability for solar electric mission analysis.

II. SPACEFLIGHT TRAJECTORY ANALYSIS

The emphasis during this period has been on continuing development of Gordon 1 and ITEM programs.

A. Gordon 1

Gordon 1 is a two-dimensional heliocentric optimization program which selects thrusting program, and propulsion parameters (VJ_o power) in order to maximize payload for a given mission. The mission must be specified in terms of arrival planet, launch date, and trip time. The program is presently in working form; effort by Dr. Gordon in this period has been directed toward adding options which make more realistic analyses possible.

The additions to the program during the past three months include

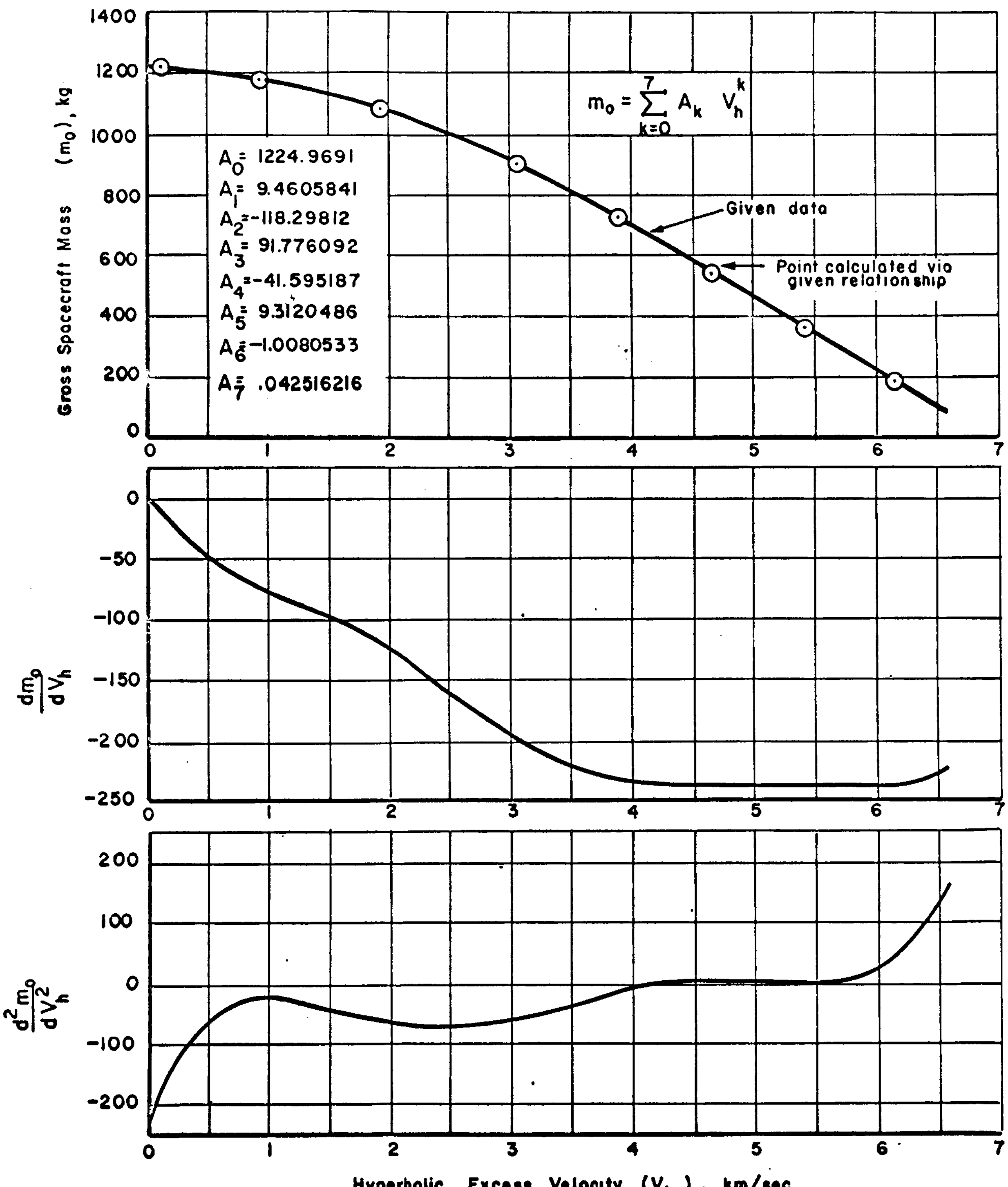
(1) Subroutines which give launch vehicle performance, ion engine performance and solar array performance. The original data was supplied by JPL in the form of curves. These curves have been matched by functions whose parameters were chosen on a least-square basis. The curve-fits are shown in FIGURES 1, 2, and 3. The functions chosen represent a compromise between a low number of terms, given a simpler expression, and a large number of terms giving better accuracy. The curve representing launch vehicle performance is not satisfactory (second derivative not sufficiently smooth) and is being changed. (The second derivative affects the optimization algorithm.) Accuracy of the curves is within one-half per cent of the data given. The launch vehicle in Figure 1 is an Atlas (SLV3C)/Centaur.

(2) Addition of ephemeris routine which computes the initial and final conditions used in the iteration, given the Julian launch date and trip time. In addition, a routine is being developed which searches the ephemeris

LAUNCH VEHICLE PERFORMANCE

Launch Capability of the Atlas (SLV3C)/Centaur for the period 1973 — 1977

Ref: N A S A, Launch Vehicle Estimating Factors for Generating OSSA Prospectus 1967, November 1966



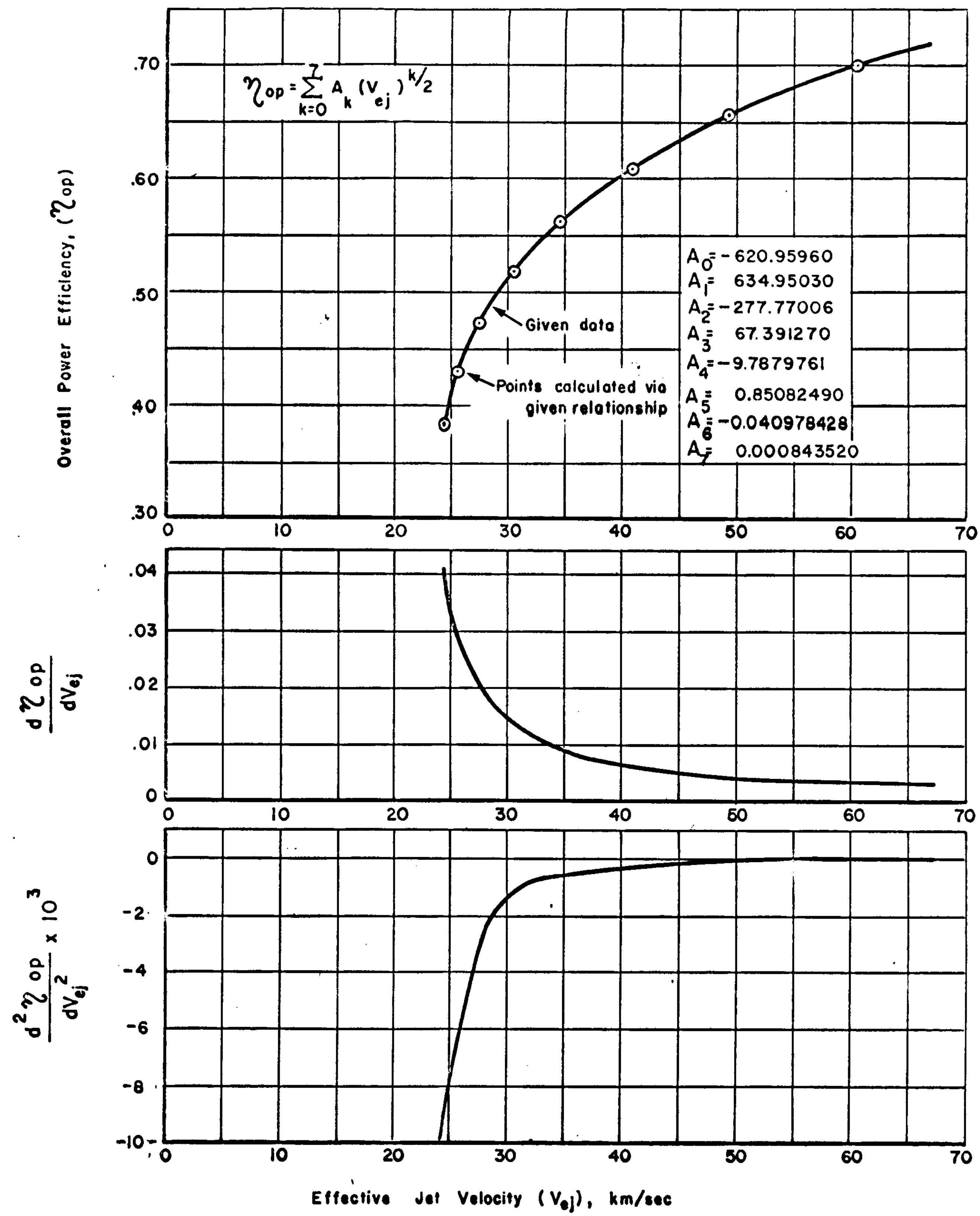
Curve Fit of Gross Spacecraft Mass Versus Hyperbolic Excess Velocity

FIGURE 1

ELECTROSTATIC (ION) ELECTRIC ROCKET PERFORMANCE

Electron Bombardment Thruster with Cesium for the Period 1973–1977

Ref: N A S A (J.P. Mullin) Letter Dated January 19, 1967

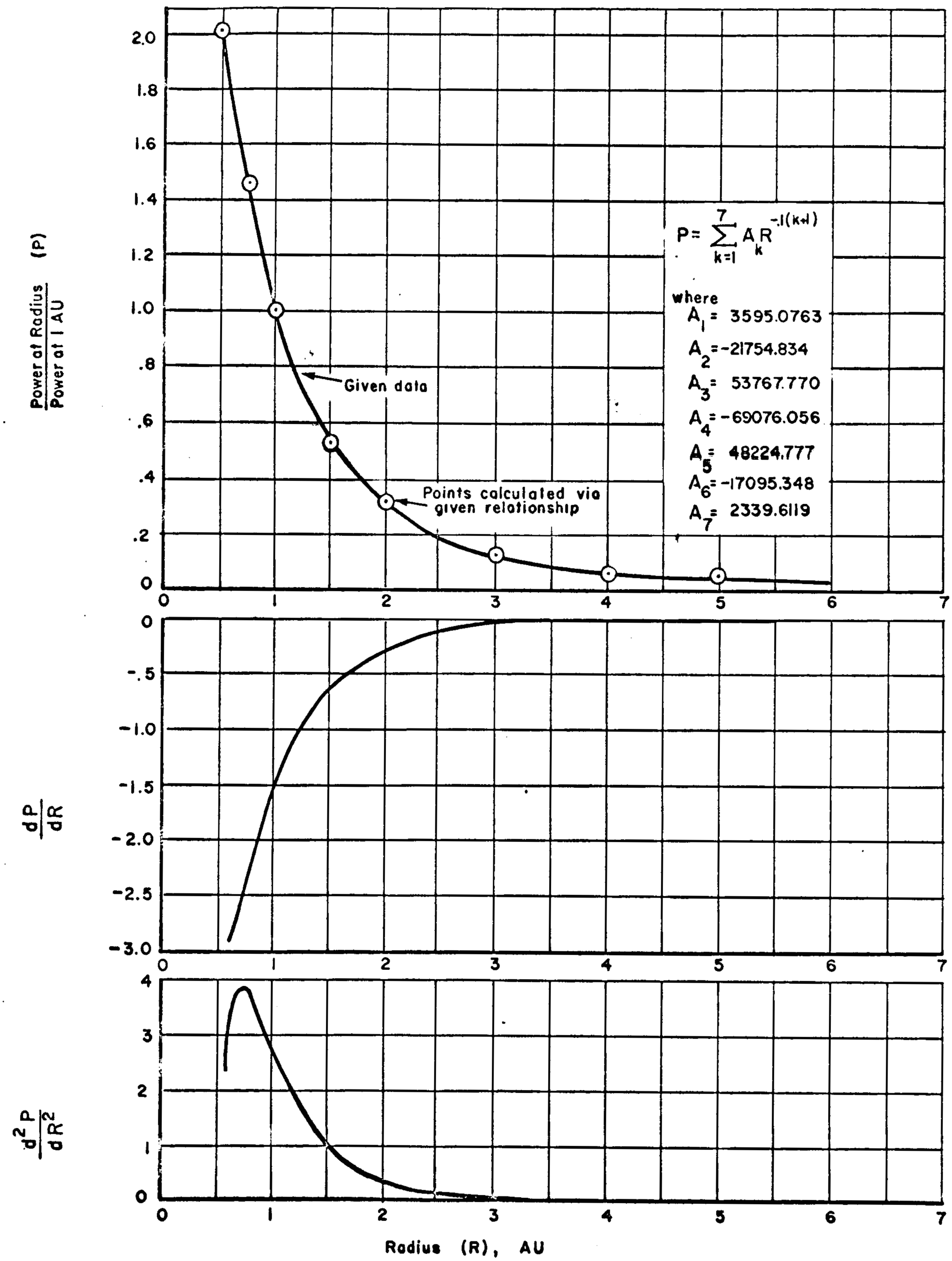


Curve Fit, Including First and Second Derivatives, of Overall Power Effiency vs. Effective Jet Velocity

FIGURE 2

Solar Electric Array Technology for the Period 1973 — 1977

Ref: Table A-3 Hughes Report SSD 60374R, December 1966.



Curve Fit of Power Versus Radius

FIGURE 3

tape for launch configurations which correspond to given boundary conditions. This will enable us to find appropriate launch dates which correspond to optimum angle trajectories.

(3) Addition of sweep capability for the following parameters: launch date, trip time, initial conditions, final conditions, jet velocity, power, initial acceleration, engine efficiency, specific power, initial mass, solar power law and C_3 . By specifying the increments and range, any or all of these parameters can be varied to determine payload sensitivity.

(4) Addition of options which allow propulsion parameters (VJ, FMO) to be held fixed or optimized.

The status of the Gordon 1 program can be summarized as follows: It is a working program which has been exercised over a certain range of realistic parameters. Considerable programming effort is still going on to add the full flexibility and comprehensiveness desired.

B. ITEM

Mr. John Campbell of AMA has been in charge of the Princeton version of the ITEM program. The principal effort has been directed toward adaption of the program for solar powered vehicles and conversion to the IBM 360 computer.

A general rewrite and cleanup has been started. The purpose for this is to obtain an interplanetary trajectory program which can be used efficiently and flexibly with existing parameter iteration and optimization techniques. An outline of these changes is as follows:

(1) Changes to increase flexibility

(a) The program has been reduced to a subroutine capable of integrating a trajectory segment. A trajectory of any configuration can be created simply by making multiple calls to the integration routine.

(b) The number of planets has been increased from four to nine.

(c) The ability to stop the trajectory precisely on a given time, flight path angle, or radius magnitude has been included. This allows more freedom in the selection of parameters for iteration and optimization.

(d) In addition to programmed thrust modes, the ability to integrate the adjoint equations has been included.

(2) Changes to increase efficiency

(a) Time has been replaced by beta as the independent variable of the integration. Beta is defined by the following equation:

$$-\beta^2/a = \theta^2$$

where a is the semi-major axis of the orbit and θ is the incremental eccentric anomaly. This change allows Kepler's equation solution to be obtained without iteration, and it allows a more favorable step size to be chosen for the numerical integration.

(b) The ephemeris routine was modified to place all necessary ephemeris data in core at the same time. This eliminates tape manipulation during the computation of a trajectory but restricts the program to computers of at least 65K words of core storage.

(c) The integrator has been changed from single step to multi-line integration. A table of 25 points is used. The value of this is:

(i) The number of Runge-Kutta steps necessary for starting is reduced. This allows starting of the sixth order integration in about onethird of the time previously required.

(ii) Updating of the table is more efficient since it is only required once every 18 steps instead of every step.

(iii) Plenty of points are available for interpolation if values are desired which are not contained exactly in the table.

(iv) Editing of the tables is more efficient.

(d) Three modes of integration (all sixth order) have been included. These are:

(i) Backwards difference predictor only.

(ii) Backwards difference predictor with a central difference corrector.

(iii) Iterative central difference corrector.

Two modes of starting are included:

(i) 4 to 1 Runge-Kutta and backward difference predictor.

(ii) Iterative central difference corrector

These modes allow any integration accuracy in the least amount of computer time.

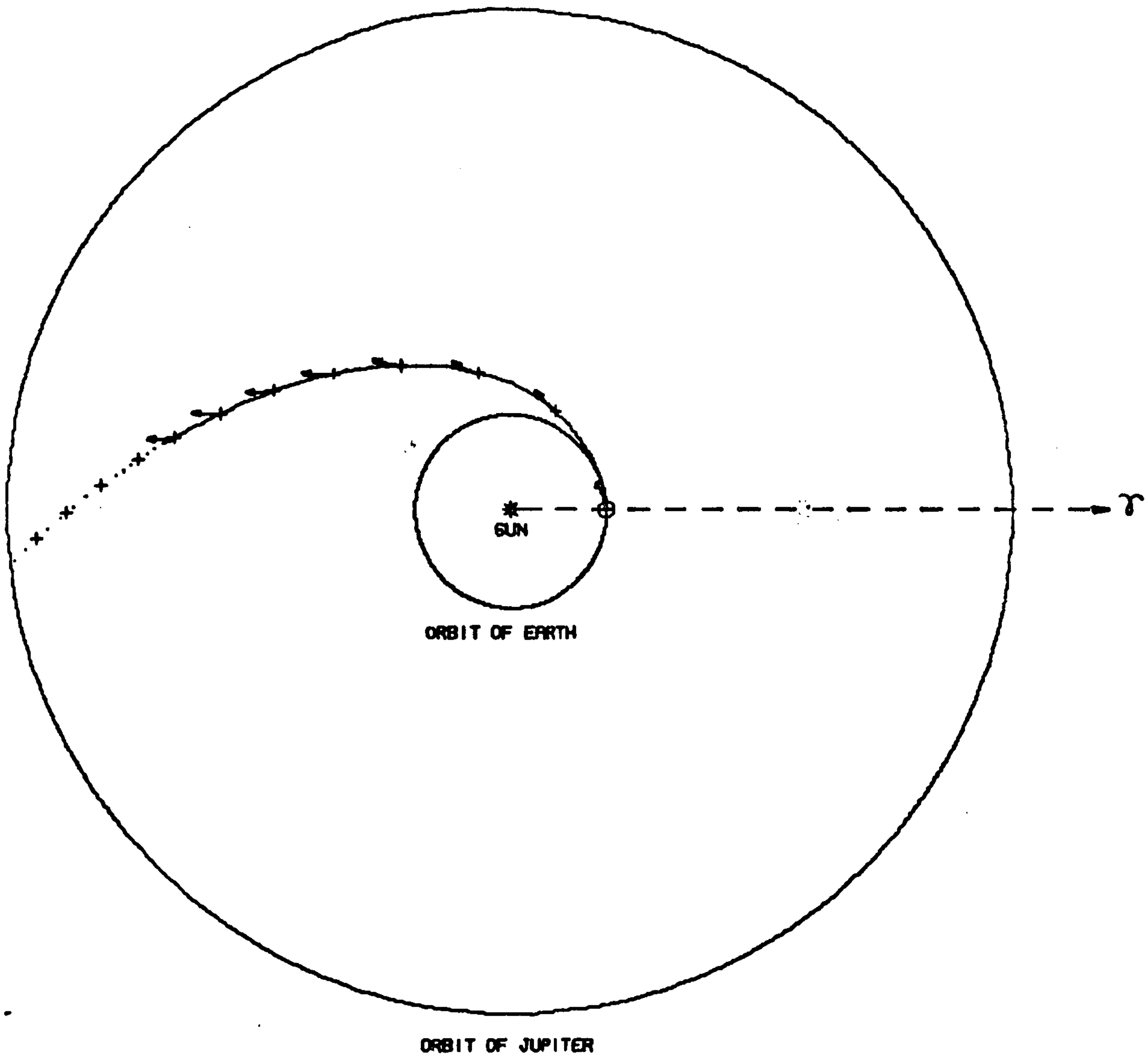
The status of this version of the ITEM program can be summarized as follows: the programming is essentially completed but needs checking and exercise. Several trajectories from Gordon 1 were checked using the 7044 version of ITEM.

III. SOLAR ELECTRIC MISSION ANALYSIS

The main effort in mission analysis during the period 1 January to 31 March 1967 has been the study of the Jupiter flyby mission. The trajectories computed optimized power level, jet velocity and hyperbolic excess velocity (C_3) as well as the thrust program. Trajectories computer were open angle (assuming Earth and Jupiter to be in circular orbits) with flight times in the range 500-900 days. (Optimum in this context means maximum payload or net mass.) Vehicle characteristics used were prescribed by JPL. All trajectories thus far have been run with powerplant specific mass α = 30 kg/kw .

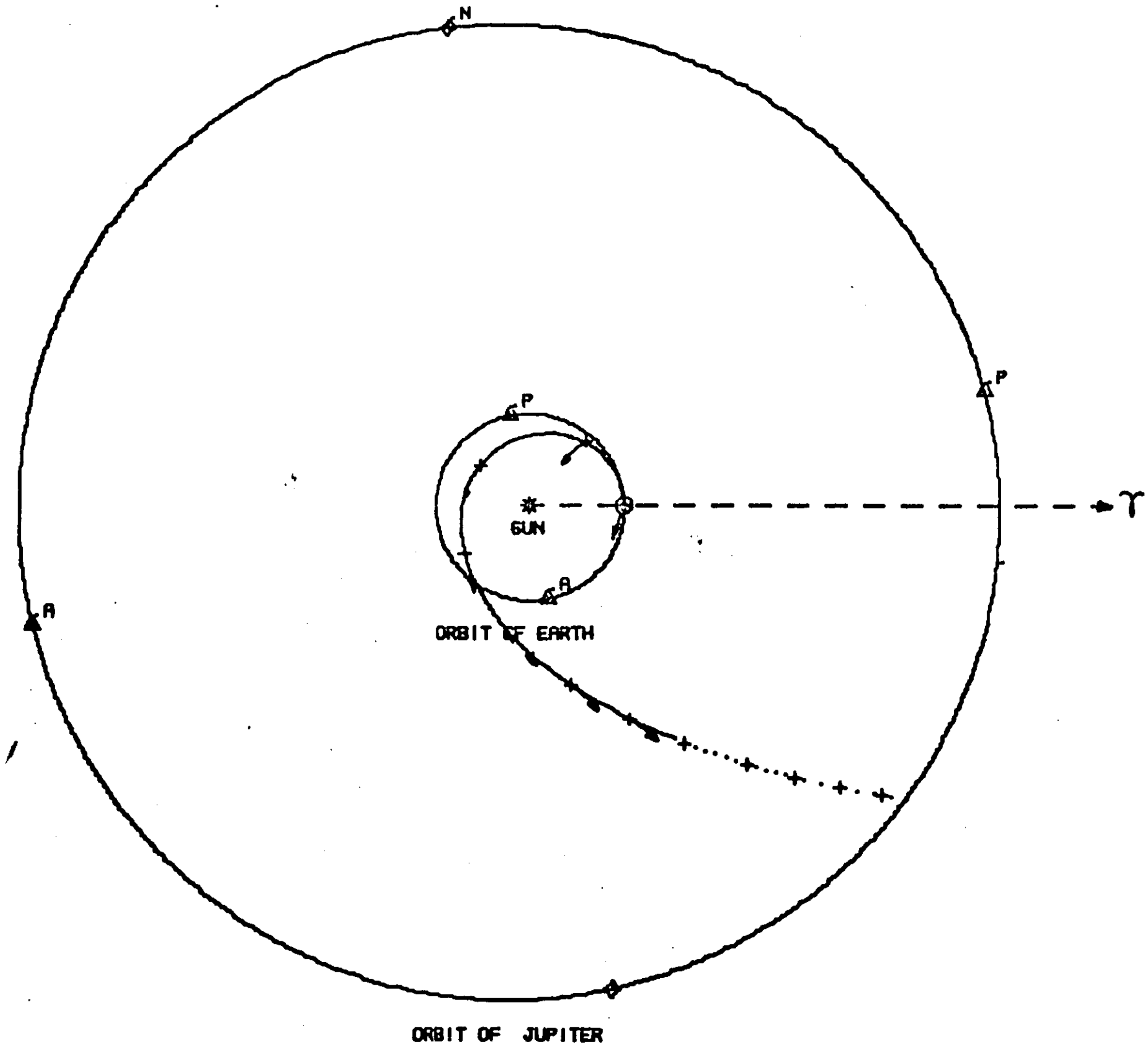
One of the more interesting results of this study was the identification of three different modes over the range of flight times investigated. Mode 1, shown in FIGURE 4, is a direct flight with thrust always acting in the general direction of the velocity and energy always increasing. Travel angles for this mode are typically four radians. Mode 2, shown in FIGURE 5, requires an initial retro-thrust thus decreasing energy and allowing the spacecraft to fall in toward the Sun. At the perihelion of this trajectory, where power is maximum, the thrust direction has swung around and is now supporting the motion and the spacecraft energy is increasing. Travel angles for this mode are typically six radians. Mode 3, shown in FIGURE 6, has three different phases where the thrust alternately supports, opposes and again supports the motion and the energy is correspondingly increased, decreased, and increased. These trajectories are typically eight radians.

The principal result, a plot of payload vs travel time, is shown in FIGURE 7. For short travel times, Mode 1 is the best; whereas, for longer



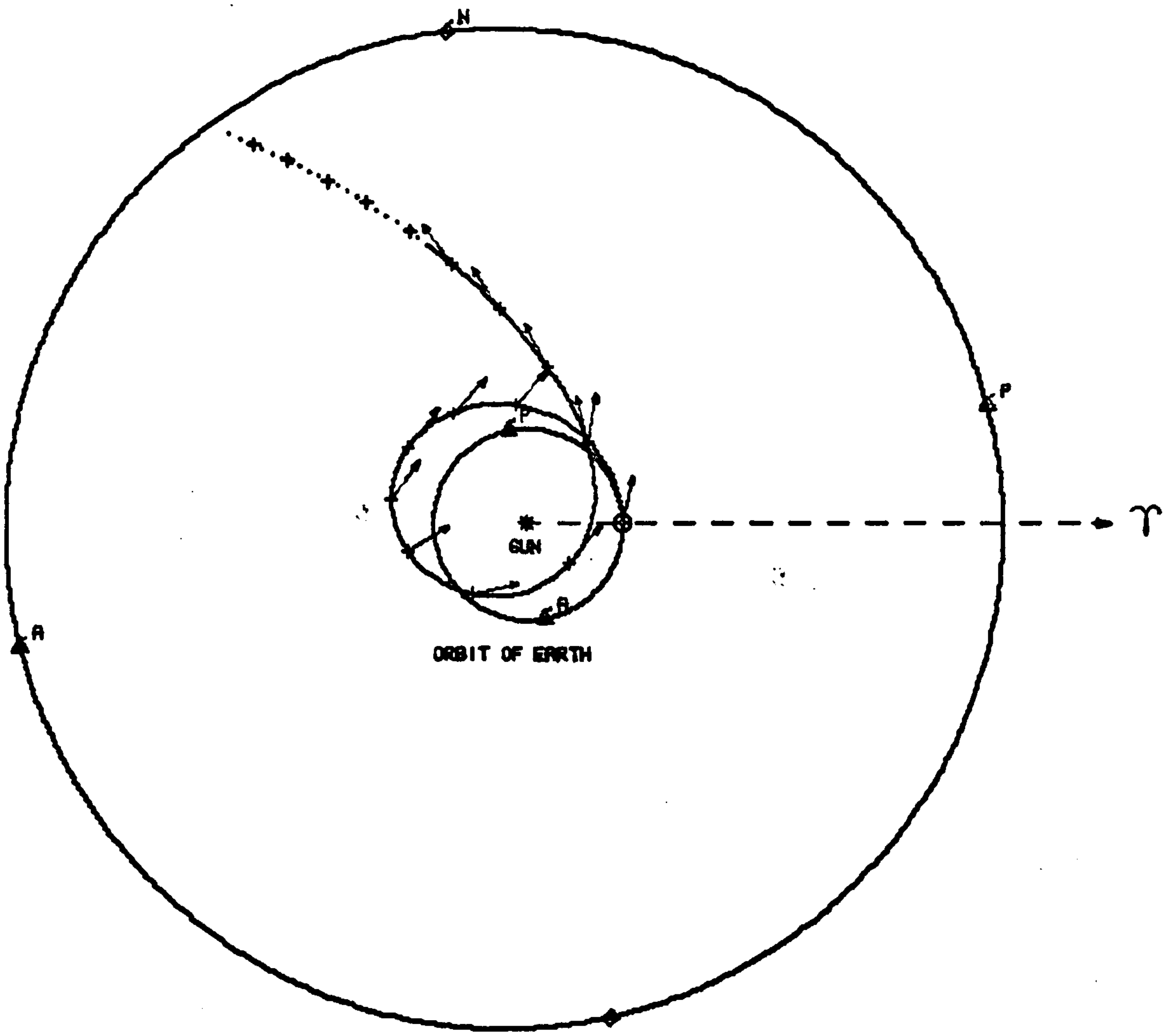
FLIGHT TIME 600 DAYS
TRAVEL ANGLE 3.25 RAD.
VJ=32361.7 M/SEC,C3=16.07 KM**2/SEC/SEC
ALPHA=.027, ETA=.5401
NET MASS=146.5 KG

FIGURE 4



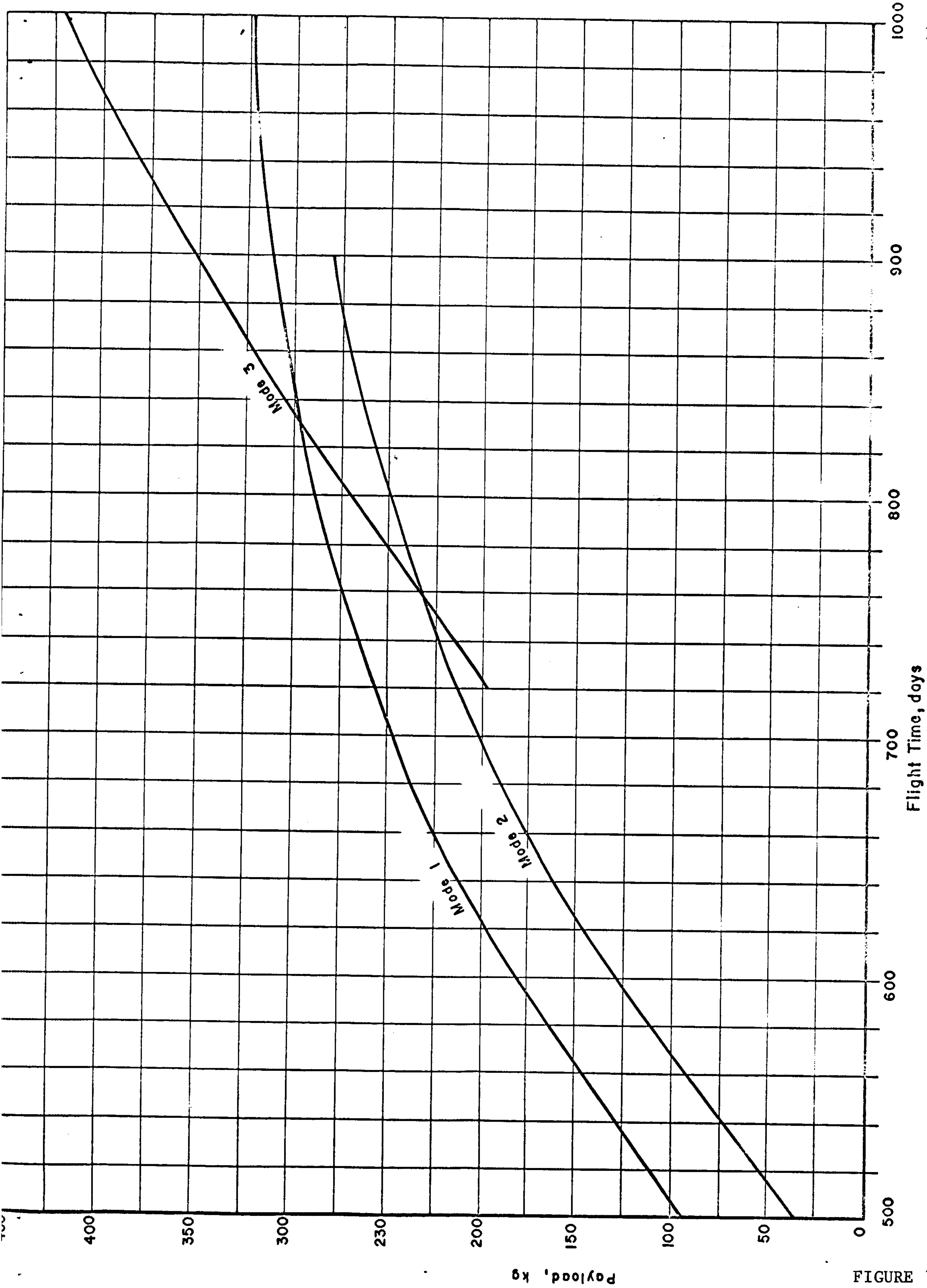
FLIGHT TIME 600 DAYS
TRAVEL ANGLE 5.65 RAD.
VJ=33904.29 M/SEC
C3=6.16 KM**2/SEC/SEC
PL=131.52 KG

FIGURE 5



FLIGHT TIME 900 DAYS
TRAVEL ANGLE 8.525 RAD.
VJ=41776.88 M/SEC
PL=353.53 KG
C3=2.14 KM**2/SEC**2

FIGURE 6

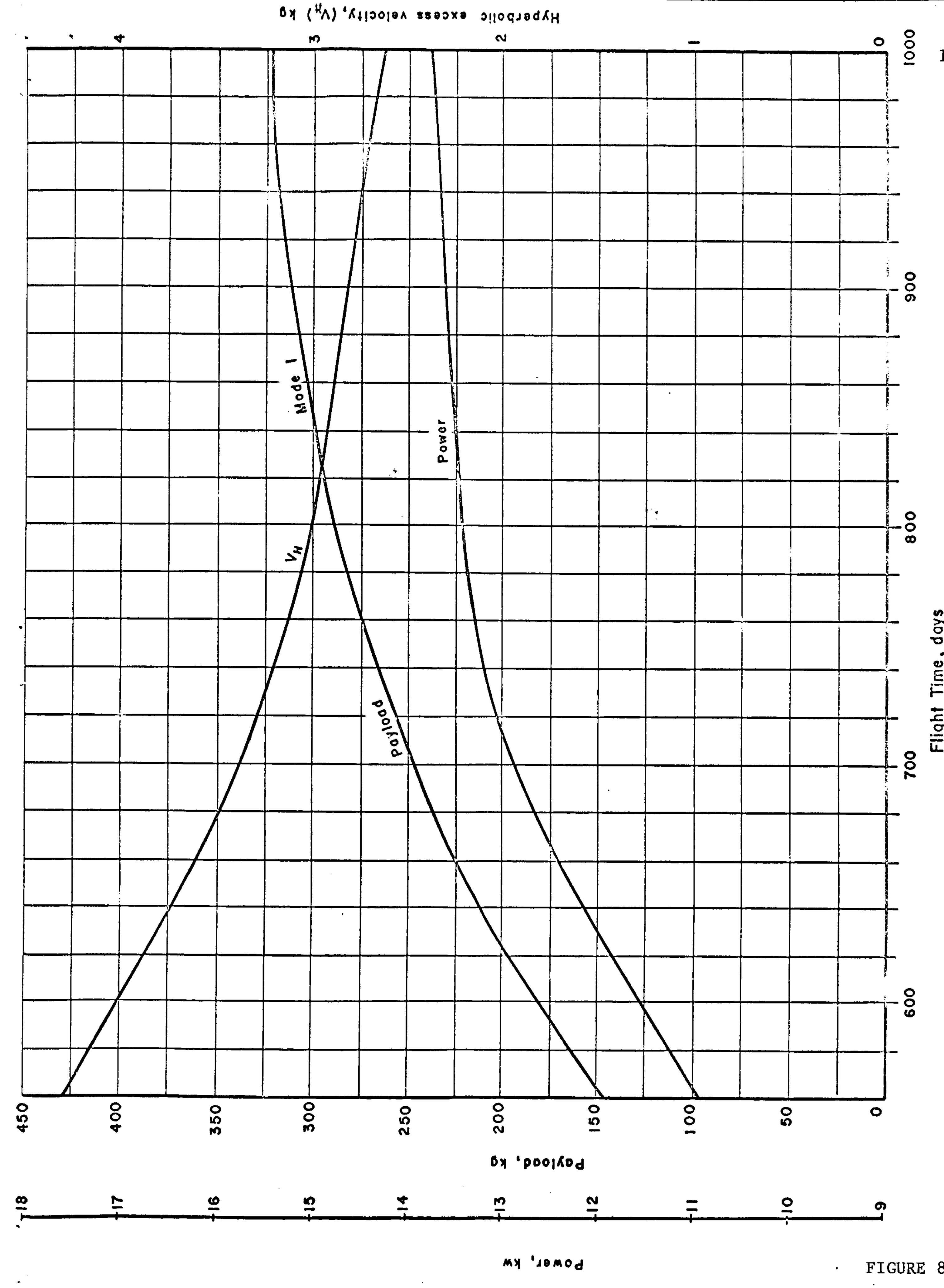


Payload vs. Flight Time

FIGURE 7

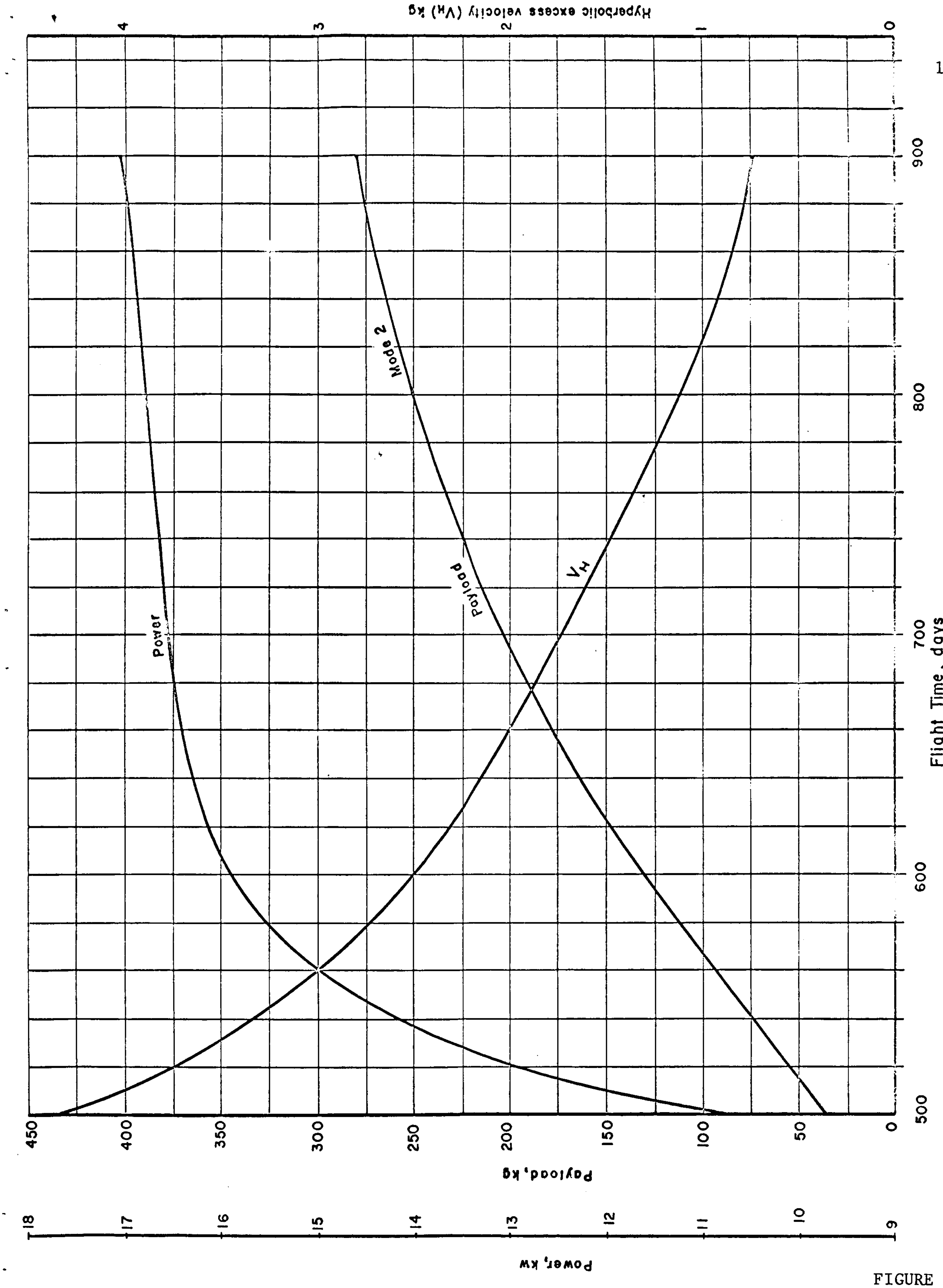
trip times Mode 3 is best. For the particular vehicle characteristics used, the crossover point is about 870 days. Mode 2 is never optimum (except locally). FIGURES 8, 9 and 10 show further details on Modes 1, 2, and 3, respectively: power, hyperbolic excess velocity and jet velocity are plotted versus trip time. FIGURE 11 shows a typical (600 day) Mode 1 trajectory profile (see FIGURE 4); similarly, FIGURE 12 shows a profile for 900 day Mode 3 trajectory (see FIGURE 6).

Further work remains to be done in determining the sensitivity of payload to off-optimum choices of parameters (VJ, power, VH) and to advances in technology (decreasing (α, increasing efficiency η).



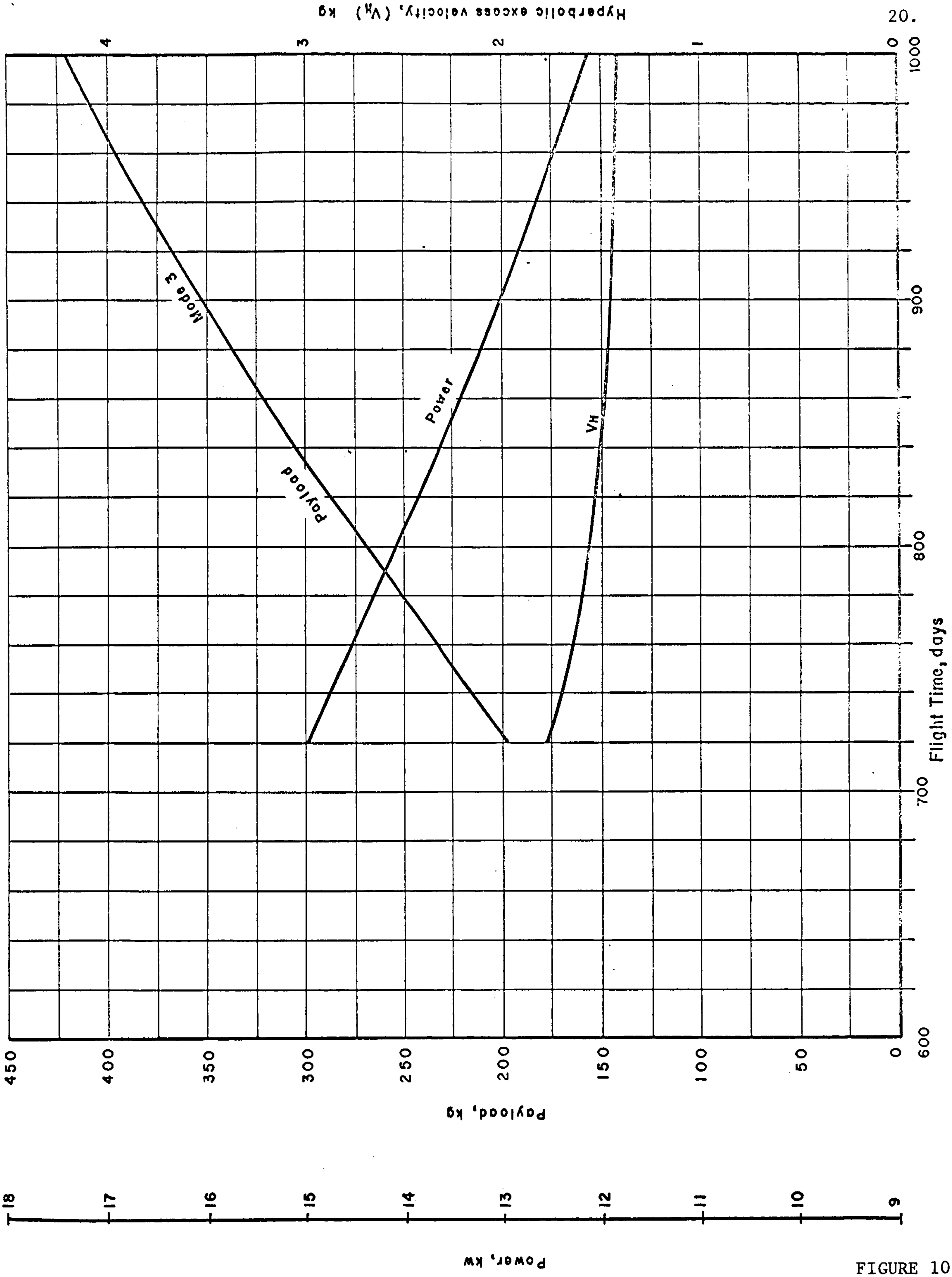
Power, Payload, V_H vs. Flight Time (Mode I)

FIGURE 8



Power, Payload, V_H vs. Flight Time (Mode 2)

FIGURE 9



Power, Payload, V_H vs. Flight Time (Mode 3)

FIGURE 10

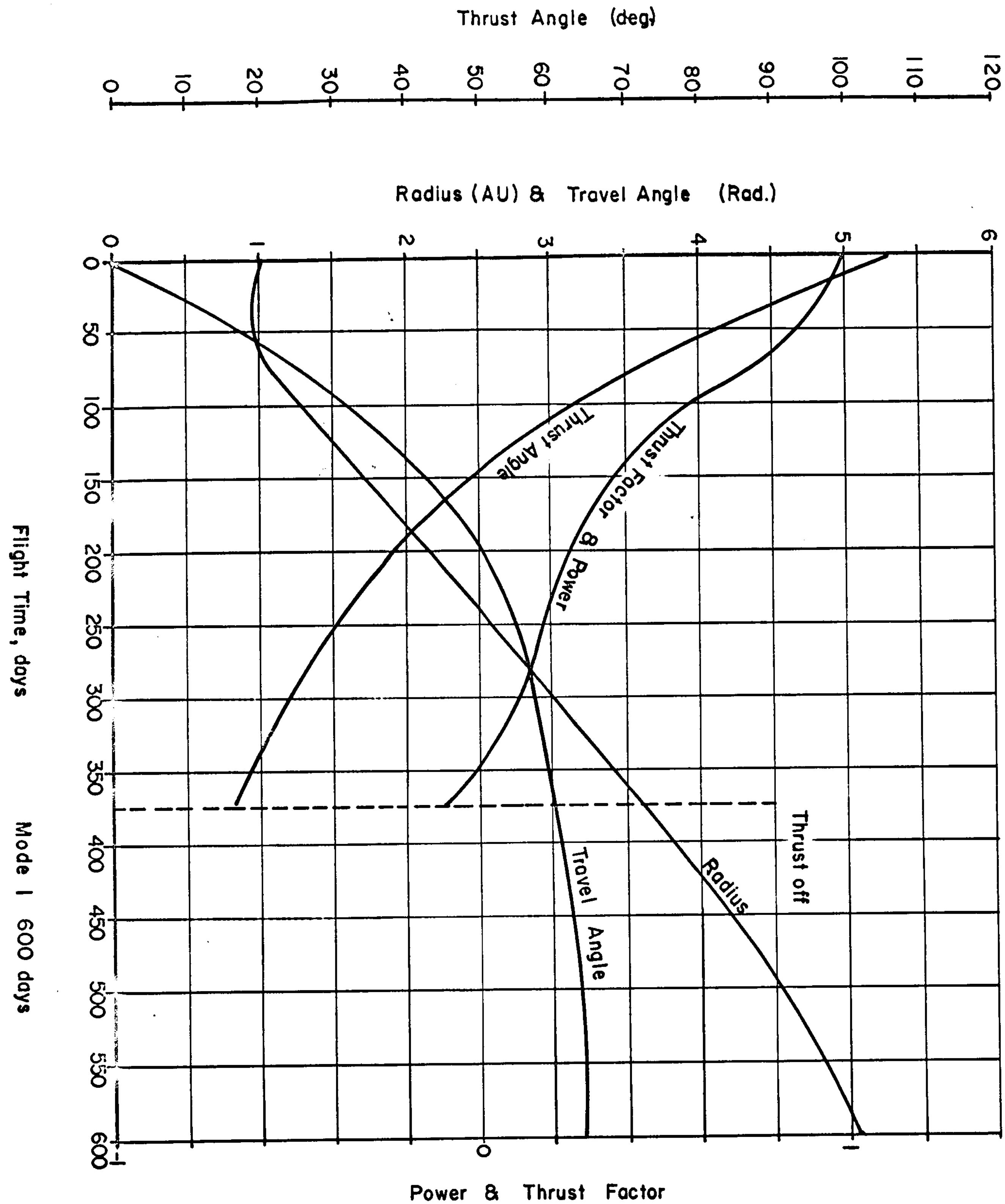

Thrust Angle (deg)
0 10 20 30 40 50 60 70 80 90 100 110 120
Radius (AU) & Travel Angle (Rad.)
0 1 2 3 4 5 6
Thrust Angle
Thrust Factor & Power
Travel Angle
Radius
Thrust off
0 50 100 150 200 250 300 350 400 450 500 550 600
Flight Time, days
Mode I 600 days
0 1
Power & Thrust Factor

FIGURE 11

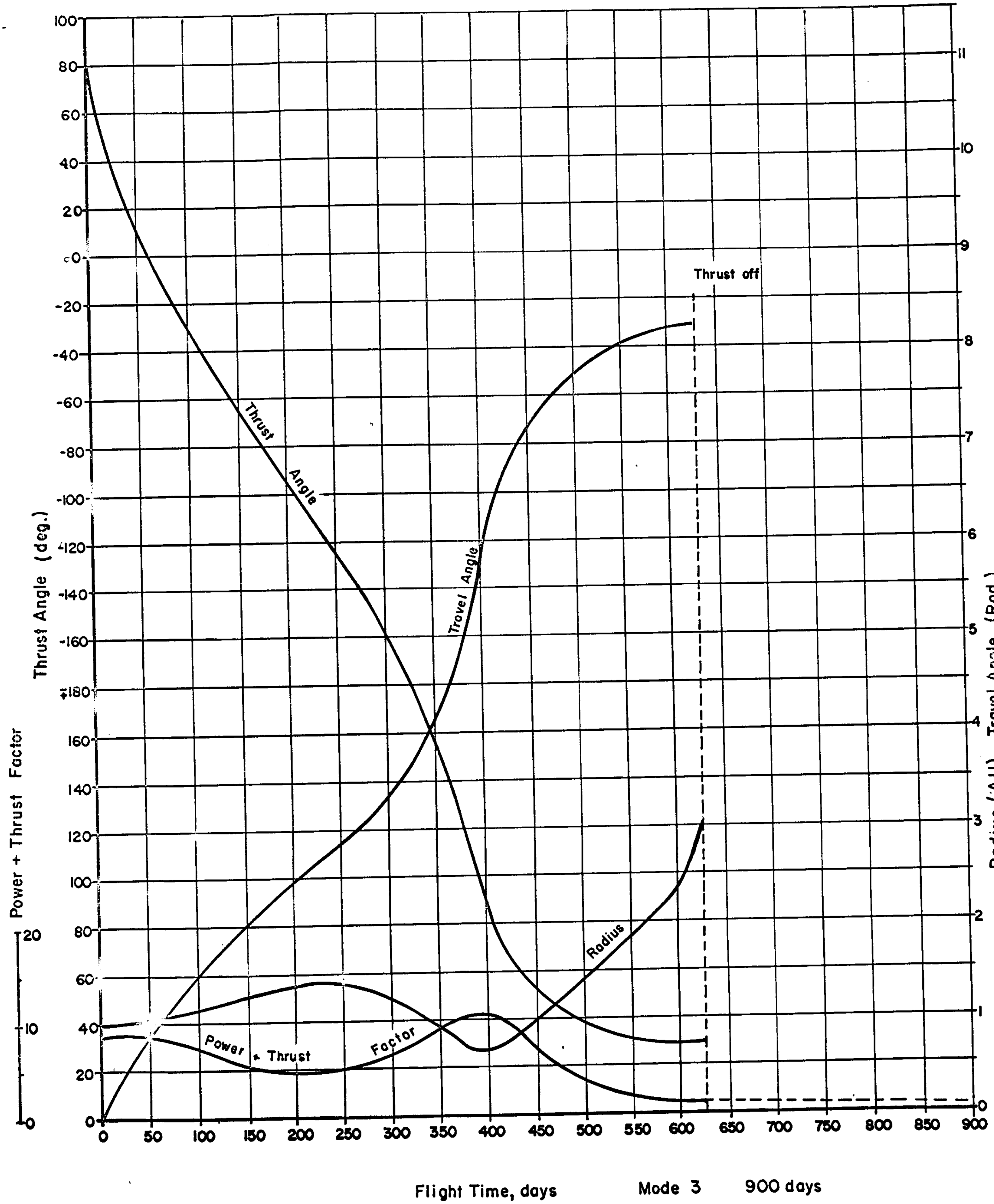

Thrust Angle (deg.)
Power + Thrust Factor
Travel Angle (Rad.)
Radius (AU)
Thrust Angle
Travel Angle
Radius
Power + Thrust Factor
Thrust off
Flight Time, days
Mode 3
900 days

FIGURE 12

PRINCETON UNIVERSITY
Department of Aerospace and Mechanical Sciences

As of 1 February 1967

AEROSPACE SYSTEMS and MISSION ANALYSIS RESEARCH (ASMAR) PROGRAM

Personnel List

Administrative	J. P. Layton, Research Leader	pt
	F. Allison, Senior Project Secretary	ft
	(, Project Secretary	ft)
	L. B. Jas, Jr. Draftsman	ft
Spaceflight Trajectory Analysis Research	P. M. Lion, Asst. Prof. (Asst. Res. Ldr.)	1/3t
	A. B. Shulzycki, Programmer	1/2t
	G. A. Hazelrigg, Grad Student (PhD Cand)	1/2t,nc
	J. P. Peltier, Grad Student (MSE Cand)	1/2t
	M. Minkoff, Grad Fellow (MSE Cand)	1/2t,nc
	R. A. Philips, Undergraduate Student '67	pt
Aerospace Systems Analysis Research	J. P. Layton, Senior Research Engineer	1/4t
	R. Vichnevetsky, Visiting Research Scientist	1/5t
	M. J. Flynn, Undergraduate Student '67	pt
	C. F. Kalmbach, Undergraduate Student '68	pt,nc
	M. J. Boyle, Undergraduate Student '69	pt,nc
Interplanetary-Planetary Mission Analysis Research	J. P. Layton, Senior Research Engineer	1/4t
	P. M. Lion, Asst. Prof. (Asst. Res. Ldr.)	1/6t
	J. H. Campbell, Sr. Programmer (AMA)	ft
	A. E. Miller, Programmer	ft
	A. B. Shulzycki, Programmer	1/2t
	G. A. Hazelrigg, Grad Student (PhD Cand)	1/2t
	J. E. Kerr, Undergraduate Student '67	pt,nc
	E. J. Sarton, Undergraduate Student '68	pt,nc
	T. E. Blejwas, Undergraduate Student '68	pt

Consultants:

L. Crocco, Professor	pt,nc
D. Graham, Professor	1/6t
J. Grey, Associate Professor (on Leave)	pt,nc
R. G. Jahn, Associate Professor	pt,nc
R. A. Phinney, Associate Professor	pt,nc
M. Handelsman, Professor (Drexel)	1/5t
A. E. Bryson, Professor (Harvard/MIT)	pt
G. Leitmann, Professor (U. of Cal., Berkeley)	pt

Subcontracts:

AMA - S. Pines, H. Kelley, T. Edelbaum, et al.	pt
RCA - C. N. Gordon	1/2t